Elasto-Plastic Behavior of Outrigger Braced Walls

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Abstract: Outriggers are commonly used in high rise buildings to enhance their behavior to lateral loads by reducing the lateral drift and wall base moments. In this paper, the nonlinear dynamic response of outrigger braced wall system to earthquake excitation is investigated. Elasto-plastic finite element model was used for the analysis considering bi-linear stress-strain relation for concrete with limited tensile strength while reinforcement was modeled as truss members with bi-linear stress-strain relation. Wall Example was prepared for 40 story buildings composed of coupled wall-column without outrigger and with outrigger at mid height. The proposed model was first verified by its results with the results of the same example as analyzed using the common ETABS commercial structural software using two common earthquake records. The difference between systems without and with outrigger subjected to two different earthquake records was investigated in terms of lateral drift, wall stresses, cracking pattern and modes of failure. The study emphasizes the fact that the existence of outrigger at mid-height enhances the drift behavior of coupled wall-column system. The stress distribution and the stress values at wall are also reduced for outrigger-braced case. Failure of wall subjected to earthquakes was observed to be delayed or even prevented if outrigger is added in addition to the prevention of development of extensive cracks which was observed in system without outrigger.

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Introduction

As buildings grow up, the control of lateral drifts developed as a result of lateral loads, especially earthquakes became of most importance. Outrigger-braced systems are reported to be one of the most effective systems in reducing the building drifts and wall moments in high rise buildings (*Ahsan Kareem et al., 1999, Stafford Smith and Coull, 1991, Hoenderkamp, and Snijder, 2003).* Outrigger system is compose of one or more deep girders at different levels of the building mobilizing the core or wall with exterior columns to enhance the lateral load resistance of buildings *(Namara, 2005 and Herath et al., 2009).* The function of outriggers is obtained by mobilizing the axial strength and stiffness of exterior columns to resist part of the overturning moment produced by lateral loading *(Shankar Nair, 1998).*

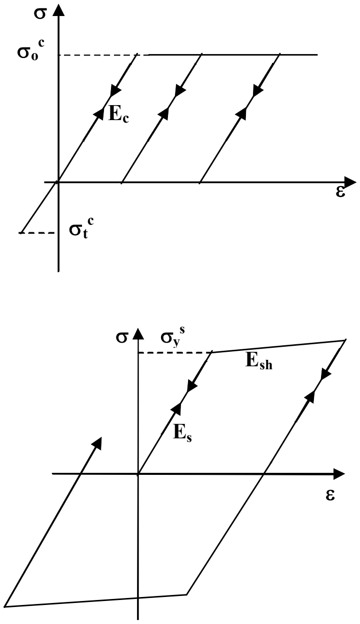
The contribution of outriggers in enhancing the behavior of high rise buildings has been extensively investigated. The system indicated an effective increase in the structural flexural stiffness (*Zhang et al., 2007)* which proved that it is very effective and powerful for buildings up to 60 stories height *(Namara, 2005)* or even more (*Ahsan Kareem et al., 1999).* Such investigations led to the development of methods for the analysis and design of outrigger-braced wall systems. *Stafford Smith and Salim, 1984* introduced an approximate method for solving symmetrical outrigger systems subject to uniformly distributed load and triangular loads enhanced by *Guo-Kang, 2010***.** Afterwards, too many investigation concerning the optimum location that lead to more reduction in drifts and moments have been carried out. *Hoenderkamp, and Snijder, 2003* used stiffness-based procedure for the analysis of braced frame buildings with internal braced frame and outer façade riggers in both ends. Equations for time period of outrigger braced walls were also introduced by *Nicoreac and Hoenderkamp, 2012.*

Optimization of the location of façade riggers in drift bases lead to the reduction of the top drift by 24.48% at optimum location for the case of uniform lateral load. For composite buildings subjected to wind loads, the existence of outriggers was also reported to reduce the top drift by34, 42, and 51 percent for the cases studied by *Fawzia and Fatima, 2010* using a finite element model. *Wu and Lee, 2003* performed the same for case of lateral triangular loads leading to an optimum location of outrigger 4 to 5 % higher than that for lateral uniform loads. *Stafford Smith and Salim, 1984* carried out a study for the optimum location of outrigger wall systems up to 4 levels using multiple regression analysis leading which can be used for preliminary design. *Zeidabadi1 et al., 2004* investigated the same concluding that the behavior of the structure can be significantly influenced by the location of the outrigger. It was also indicated that in most ordinary cases the best location of outriggers to minimize top drift is somewhere between 0·4 to 0·6 of the height of the structure. Increasing the rigidity of outriggers to very high vales which results in high restraining moments leading to weak story have been studies by *ZHANG et al., 2007* by deriving equations for the optimum location of outrigger for min. top deflection and mutation moment. They concluded that optimization analysis based on actual rigidity is very important and that infinite rigidity assumption affects the results. Other systems considered as "virtual" outriggers for tall buildings instead of conventional outriggers as belt trusses and basements had been also discussed by *Shankar Nair, 1998.* As discussed almost all studies surveyed considered the linear analysis and optimization of outrigger braced systems subjected to lateral static loads.

In this paper, the elasto-plastic dynamic behavior of outrigger braced walls is investigated. Bi-linear material models are incorporated in a Dynamic Elasto-Plastic Finite element program (**DEPF**) especially developed (Hanaa*, 2005*) Example wall of 40 story composed of rigid wall and external column with practical dimensions was prepared. One outrigger at mid-height is added to mid-height of the wall which is, as reported (*Wu and Lee, 2003 & Zeidabadi1 et al., 2004),* the optimum location for optimized wall behavior. Two earthquake records *(El-Centro, 1940 and Kobe, 1995*) were selected and normalized to PGA of 0.2g as the common seismicity of Middle East region. Time history analysis was carried out leading to detailed results of lateral drift, wall stresses and cracking patterns at each time step up to failure. Results were thoroughly investigated and conclusions were driven concerning the enhancement resulting for the addition of outrigger.

Model for Dynamic Elasto-Plastic+96 .3333 Finite Element

The model for dynamic non linear analysis composed of four node quadratic elements for concrete and two node truss element or reinforcement bars was adopted. Concrete is assumed to be a homogeneous and isotropic material prior to its cracking or yielding in state of plane stress. The material model of concrete is based on bi-linear stress strain relationship with elasto-plastic behavior in compression and limited tensile strength considering the crack process. Simple bilinear stress-strain curve with strain-hardening is employed for steel reinforcement. The hysteretic response curves for the materials are presented in Figure 1, (*Agrawal et al., 1981*). The model assumes that each element can possesses two orthogonal cracks for which their orientation is fixed during the analysis and is determined by the orientation of first crack formed and with the effect of Poisson's ratio neglected after *cracking Elmorsi, 1998.* In addition to the single set of open cracks considered, the material model provides for five other crack configurations resulting in six possible crack configurations no cracks, one set of open cracks, one set of closed cracks, one set of open and one set of closed cracks, two set of closed cracks, and two sets of open cracks.



a) concrete

Figure 1. Uni-axial stress- strain curves for cyclic loading (Agrawal *et al.*, 1981)

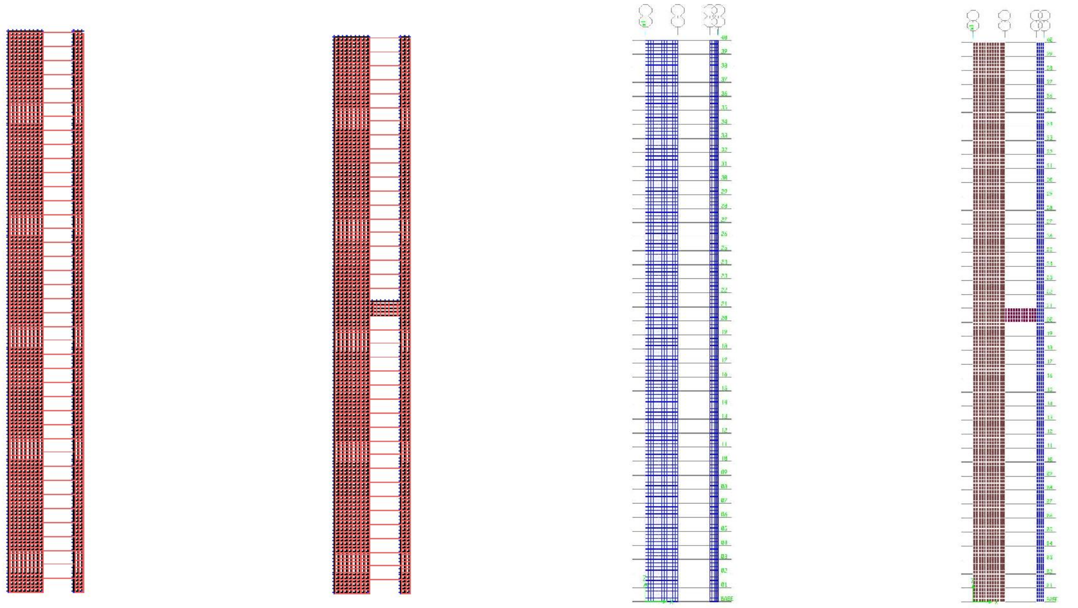
Considering the above-mentioned material model, nonlinear time history analysis was carried out to solve the equation of motion of the system shown in Eqn. 1using the known implicit step-by-step, β-3 algorithm (*Akl, 1989).*

$$[M]_{n\times n}\{\ddot{U}\}_{n\times 1}+[C]_{n\times n}\{\dot{U}\}_{n\times 1}+[K]_{n\times n}\{U\}_{n\times 1}=\{R\}_{n\times 1} \qquad (1)$$

Where N= number of degree of freedom; [K] = stiffness matrix; [C] = damping matrix; [M] = mass matrix; and {U}, $\{\dot{U}\}$, $\{\ddot{U}\}$ nodal displacement, velocity and acceleration respectively. Tow famous earthquake records *(El-Centro, 1940 and Kobe, 1995*) are used in the analysis. Horizontal components are only used after being normalized to 0.2 g which is the design PGA in the Middle East region.

The Effect of Outriggers and verification of the model

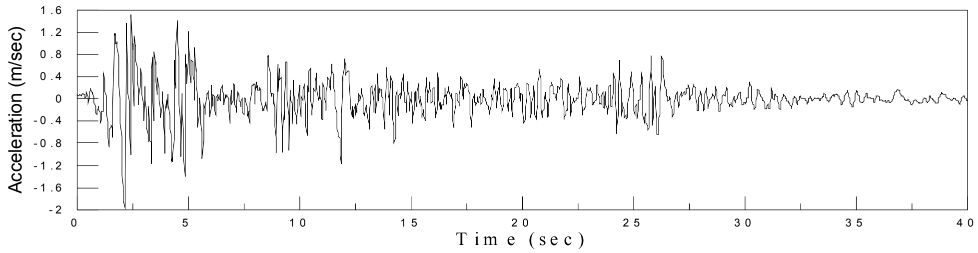
A model for coupled wall-Column system without and with outrigger at mid-height was prepared for investigating the effect of outrigger existence and the verification of our mathematical model. The same problem was modeled using the common structural analysis software (ETABS) to confirm the wall design and verify our model. The finite element meshes of both systems are shown in Figure 2. The example system is 40 stories, 4 m height each with 500x8000 mm wall, 800x2000 mm column separated by 8000 mm. The outrigger was added in the 21st story full height with dimensions 400x4000 mm. Two earthquake records (*ElCentro, 1940 and Kobe, 1995*) are used to carry out dynamic time history analysis of the wall examples. Both acceleration records were normalized to PGA of 0.2g to suit the seismicity of the Middle East region as shown in Figure 3.



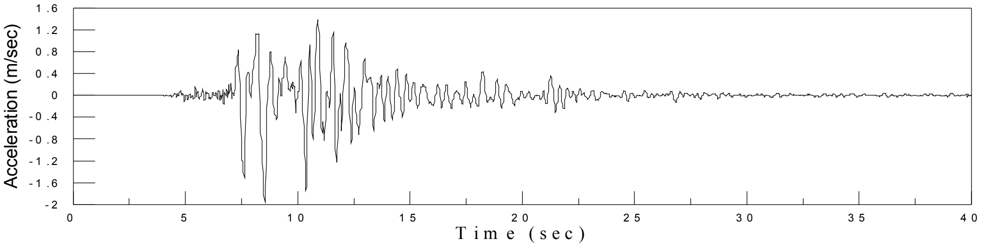
Without Outrigger ***With Outrigger*** ***Without Outrigger*** ***With Outrigger***

a. DEPF Model ***b. ETABS Model***

Figure 2. Finite Element Model



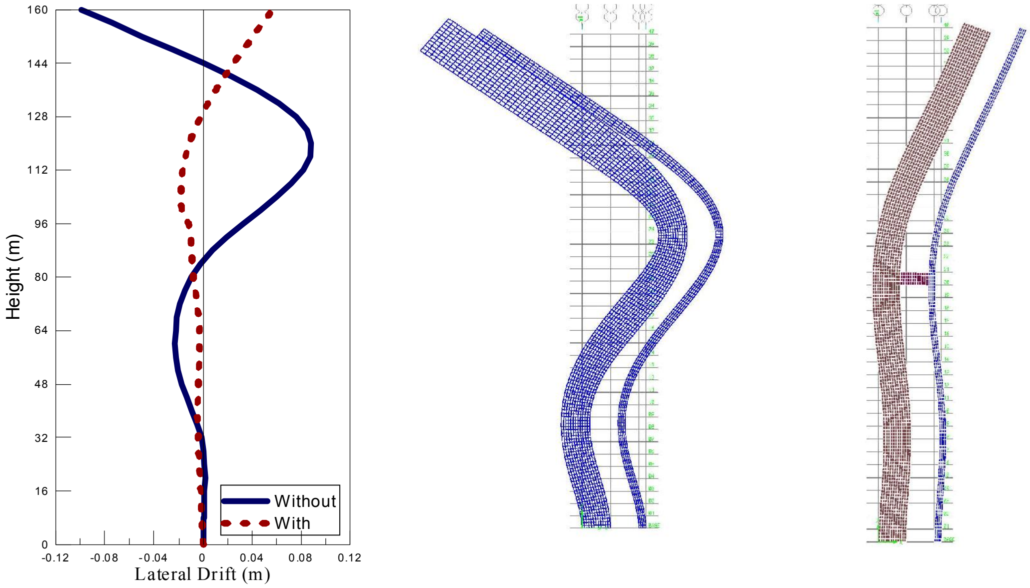
a. El-Centro, 1940



b. Kobe, 1995

Figure 3. Earthquake records

Figure 4 illustrates the effect of the existence of outrigger on the lateral drift distribution of the wall at specific time subjected to El-Centro earthquake at which the lateral displacement is plotted against the wall height at 5 sec time. Comparing the results of the proposed model (Figure 4.a) with that resulted from the ETABS model (Figure, 4.b) illustrates that the shape of the lateral displacement distribution is approximately identical. this can verify our proposed model knowing that the little differences may resulted from the nonlinear nature of our model. As shown in the Figure, the existence of outrigger changes the lateral drift distribution and values. While the original wall with outrigger tends to follow the fundamental mode shape, walls without outrigger tends to follow other mode shapes. This can be attributed to the flexible nature of the original wall and the increase in stiffness in case of adding the outrigger. Time period values of 9.85, 5.75 seconds for the original and outrigger braced walls, respectively, may clarify this fact. The value of maximum lateral drifts are more affected as illustrated in Figure 5 which plots the time history of lateral top displacements of walls considered subjected to El-Centro earthquake. While lateral top displacements are close for the two cases in the first time steps, the difference between them is significantly increased for later times. The maximum lateral top displacements of the outrigger braced system were reduced by 40 percent of that for the original wall indicating the change of wall stiffness resulting from the addition of outrigger.



a. DEPF Model *Without Outrigger* *With Outrigger*

b. ETABS Model

Figure 4. Lateral Displacement Distribution El-Centro Earthquake (at 5 sec)

The effect of the existence of outrigger on the Elasto-Plastic behavior of wall systems can be more illustrated in Figure 6. The crack pattern of the wall subjected to EL-Centro earthquake at times 5, 15, and 30 seconds are plotted in the figure. As shown, after 5 seconds, the original wall develops lots of cracked especially in the middle of the upper half of the wall while the outrigger braced one develops very few cracks at the outrigger ends. The location of original wall cracks can be attributed to the fact that the tensile stresses acting on this part are more as the weight of the wall transforms these stresses to compression in the lower parts. For wall system with outrigger, the expected large coupling force in the outrigger led to the development of few cracks at the ends of outriggers resulting from the diagonal tension as a result of shear forces. The behavior of the upper part of the wall is totally changed as results of stiffening action of the existence of the relatively stiff outrigger leading the crack free upper part of the wall. After 15 seconds, as the wall nonlinear behavior begins to control its cracking pattern, too many cracks were developed along the overall wall height for the original wall case. These cracks are more extensive at wall base and at the upper half of the wall. Wall with outrigger suffers very little cracks compared with the original one. These cracks are concentrated in the outrigger due to coupling shear, wall base due to the existence of maximum moment, and at the upper half due to the effect of tensile stress. Cracks are more propagated in the coupling outrigger and different wall locations for the outrigger braced wall at the end of 30 seconds while the original wall was totally collapsed at this time. This certifies the merit of using outriggers to elongate the life of the wall system during earthquake excitation.

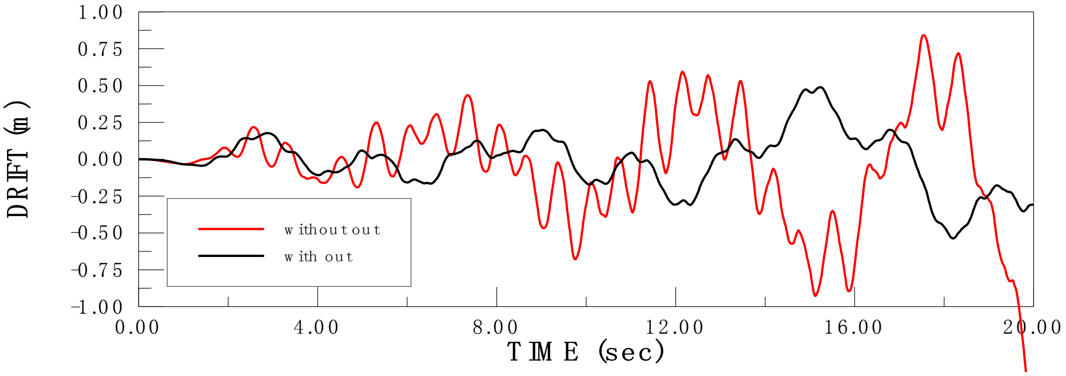
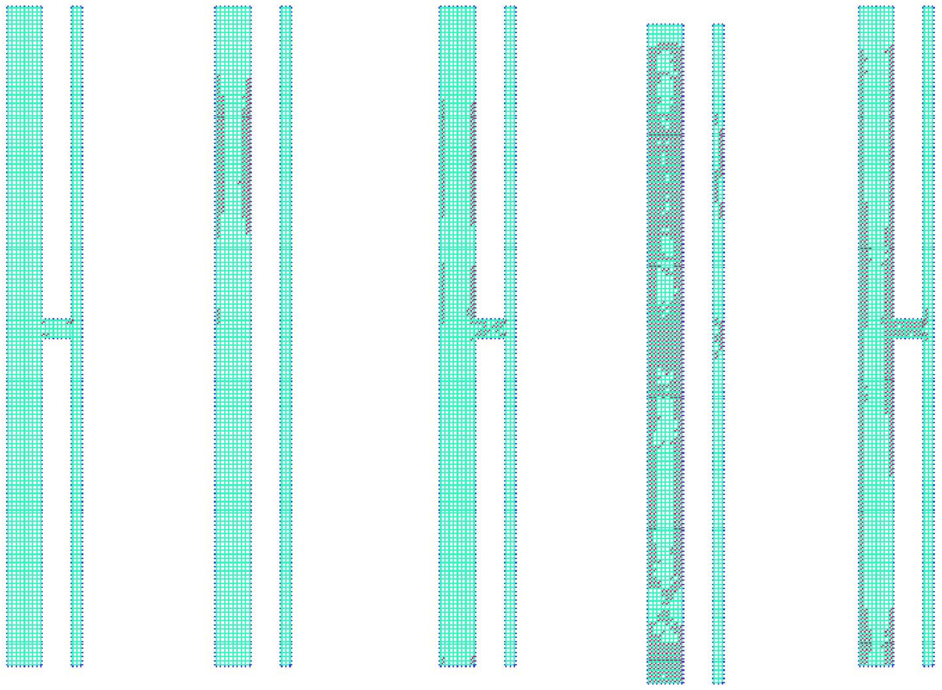


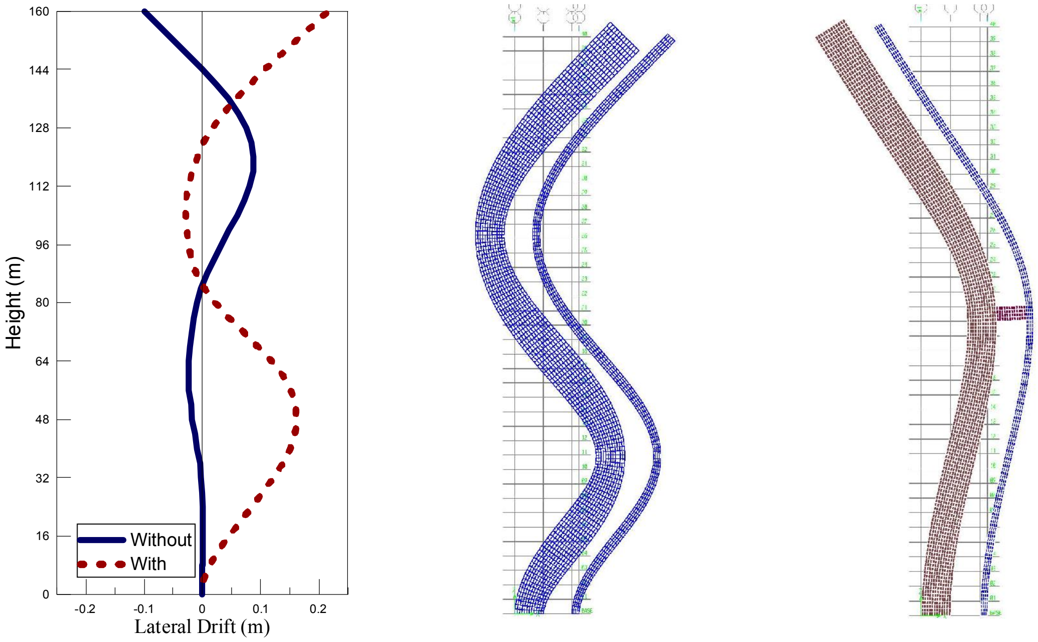
Figure 5. Time History of the Lateral Top Displacement EL_ Centro earthquake.

The same investigations can be observed for Kobe earthquake (1995) through Figures 7 to 9. Figure 7 verifies again the proposed model through the comparison with ETABS results and illustrates also the change in lateral drift distribution along the wall height for each case. The big difference between drift values between the two cases are observed from Figure 8 showing the top displacement time history giving a reduction of the maximum displacements by about 67 % when using outrigger compared to the original wall case. The crack patterns of the walls shown in Figure 9 lead to the same conclusion about the effect of adding the outrigger to wall system. Both walls are crack free during the first 5 seconds and developed cracking pattern at 15 seconds which differs considerably for the two cases as shown. At 30 seconds, although the original wall continued without failure, the extensive cracked shown in the figure indicates its relative weakness compared to the outrigger braced wall which still has little cracks at separate locations.



With Outrigger *Without Outrigger* *With Outrigger* *Without Outrigger* *With Outrigger* *Without Outrigger*
At Time (5 sec) At Time (15 sec) At Time (30 sec)

Figure 6. Crack Pattern at Different Times El - Centro Earthquake



a. DEPF Model

Without Outrigger With Outrigger

b. ETABS Model

Figure 7. Lateral Displacement Distribution Kobe Earthquake (at 15 sec)

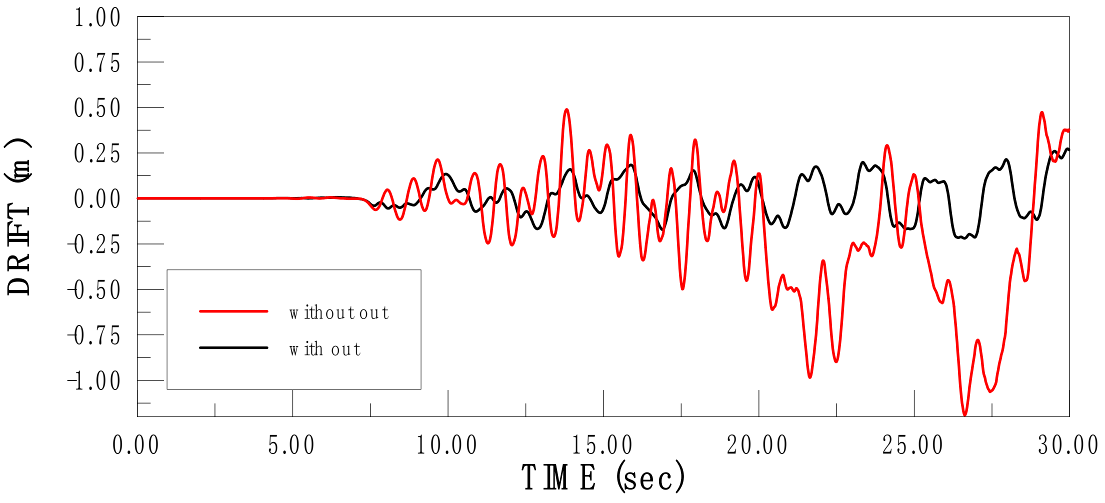


Figure 8. Time History of the Lateral Top Displacement Kobe earthquake.

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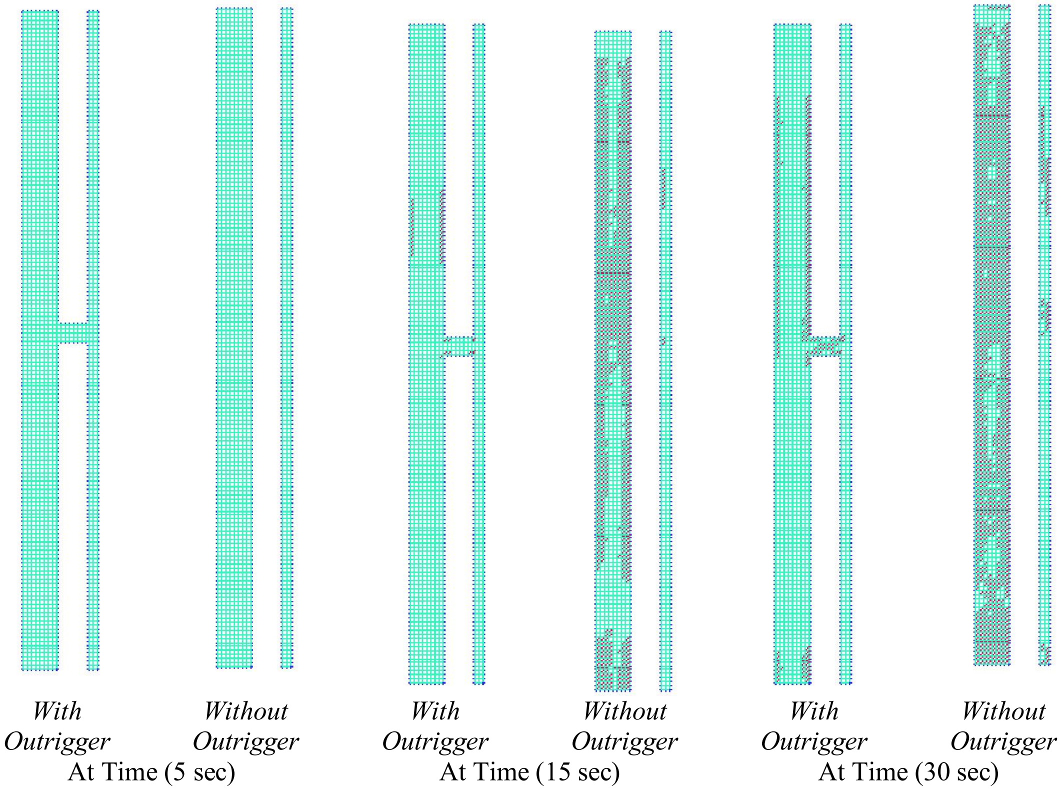


Figure 9. Crack Pattern at Different Times Kobe Earthquake

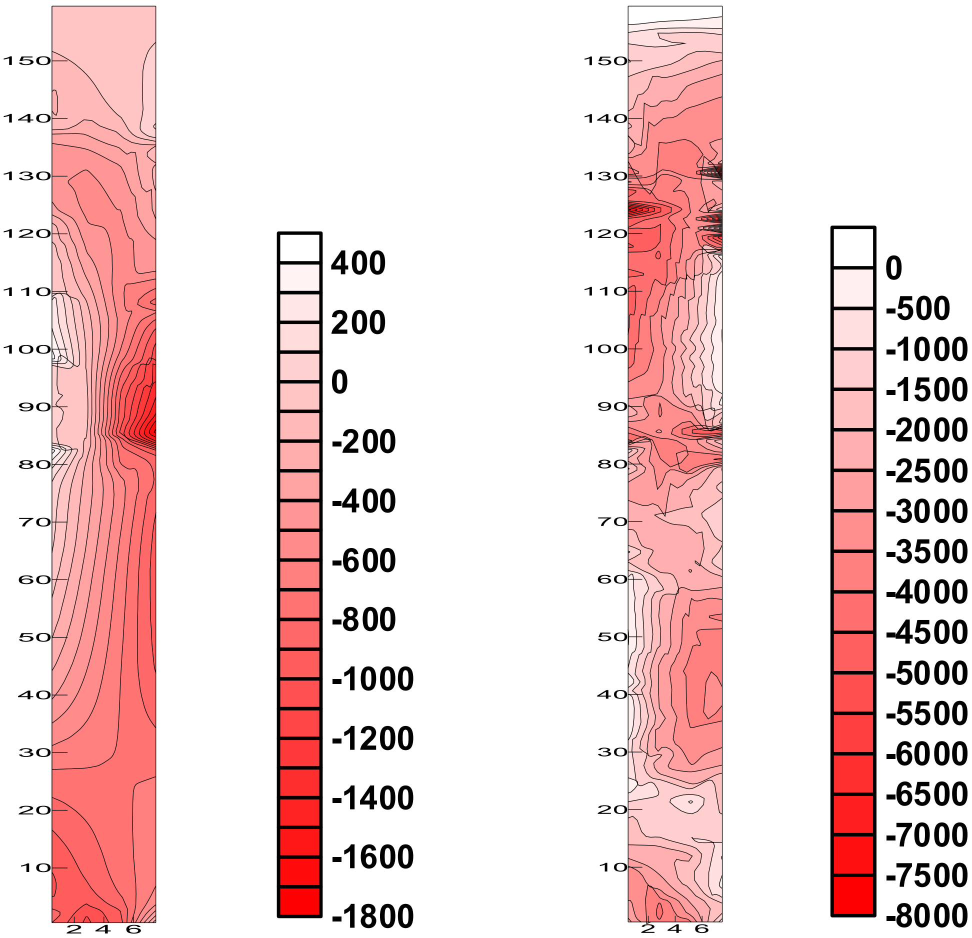
The effect of outrigger existence on normal stress distribution in the wall part is shown in Figure 10. Wall part is selected as it constitutes the main part at which cracks are developed for both cases for which this clarification is carried out. In the Figure, normal stresses are plotted through the wall at specific time (15 seconds) at which extensive cracks are observed especially for the case of original wall without outrigger. At that time, as clear from the plot, wall without outrigger suffers too much normal stresses in compression exceeding the strength of the use concrete which means that cracks are developed at these parts. also, too many locations indicates zero stresses which means that these elements are cracked during previous time steps leaving no stresses at elements with opened crack which explains the extensive crack pattern of the original wall at this time. For wall with outrigger, the situation is different such that smooth contours exists with lower limits of stresses values. Compressive stresses, as shown, is much lower than the concrete compressive strength while tensile stresses are developed indicating that most elements remain without cracks. Zero stress elements indicating cracked parts are observed near the outrigger level as previously discussed in the crack pattern.

Summary and Conclusions

The behavior of outrigger braced walls was investigated through dynamic elasto-plastic finite element analysis using the computer software especially developed (DEPF). Concrete was repented by four node quadratic element with bi-linear behavior in compression and limited tensile strength and reinforcement was represented by bar element with bi-linear behavior including strain hardening. The proposed model was verified by comparing its results in elastic zone with the results of model developed using well known commercial software (ETABS). Comparing the results of walls without and with outrigger resulted in the following behavior conclusions:

- The drift behavior of walls is considerably enhanced as result of adding an outrigger at mid height of the building such that the lateral top drift is reduced by 40% to 67% according to the earthquakes used
- The existence of outrigger lead to relatively high stiffness of the wall giving lower fundamental period of the wall which results in leading the wall to follow the fist mode of vibration. For the flexible wall without outrigger, the wall obeys later modes.

- Stress distribution in walls is affected in great manner by the existence of outrigger. walls without outriggers suffer very large values and sharp distribution of stresses while walls with outrigger has smooth low value distribution of stresses at almost all times during excitation.
- As the wall is excited by ground acceleration, outrigger-braced walls develop very few cracks compared with walls without outrigger which can be attributed to the difference in stresses discussed above. The development of extensive cracks in case of walls without outrigger lead to early failure of the wall during earthquake while walls with outrigger complete the earthquake overall period with relatively few cracks and no collapse.



With outrigger *Without Outrigger*

Figure 10. Normal Stresses Contours of wall part at time 15 seconds

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